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BRAKE-BY-WIRE PROGRAM

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14. ABSTRACT
Two design iterations for electric calipers and two systems (full brake by wire and hybrid brakes) were developed for use on a ground vehicle. The program demonstrated a fully integrated electric caliper and full brake-by-wire system on a sports utility vehicle (GM Envoy). A variety of full brake-by-wire design options were investigated. Specific areas that were explored and developed included high temperature electronics, electro-mechanical actuation technologies, reconfigurable controls, robust and low cost sensors, fault-tolerant systems, and high reliability wiring and connectors. Significant technical challenges remain before brake-by-wire technology will be available on vehicles in production; however, a significant step toward producibility was made in this effort.

15. SUBJECT TERMS
Brake-by-wire, high temperature electronics, electro-mechanical actuation, reconfigurable controls, robust and low cost sensors, fault tolerant systems, high reliability wiring and connectors

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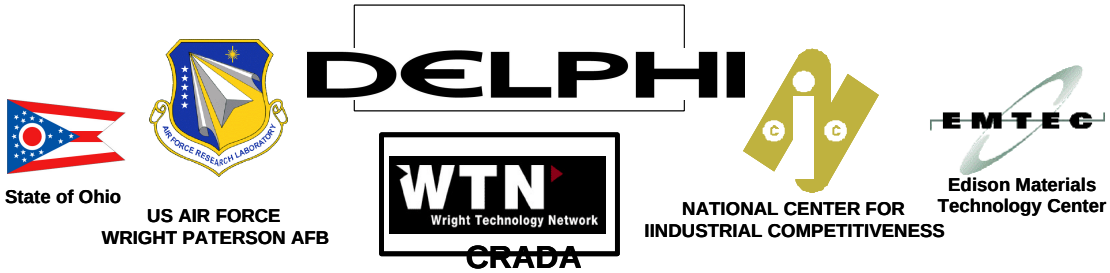
Introduction

Acknowledgement

The following organizations contributed to the successful completion of this project by assisting with funding as well as from an administrative, project management and Engineering perspective

- WTN: Wright Technology Network
- NCIC: National Center for Industrial Competitiveness
- EMTEC: Edison Materials Technology Center
- AFR: Air Force Research Laboratories, Dayton
- State of Ohio
- Delphi Corporation



Report Objectives

This report represents the last deliverable to be met to close out the federal segment of the BBW project and is designed for public release.

Project Context

The development of an electric brake caliper and associated systems for automotive application represented a significant commitment of Delphi Engineering resources. Progress made as a result of this project will give Delphi the capability to pursue the application of this technology globally.

Benefits of Project

The Federal and State of Ohio sponsorship along with the Delphi share allowed more resources to be engaged in the project than would have been feasible without Delphi external sponsorship. This enabled faster progress and allowed Delphi to be competitive (even beat competition in some areas) in the development of Brake by Wire technology.

Full Brake by Wire will likely not be in production before 2010, but a significant spin-off of the development project was the development of Hybrid Brake technology (front conventional hydraulically based brakes are combined with rear axle electrically actuated brakes).

Customer feedback was enthusiastic and significant interest for production was expressed. Commercial challenges remain however but Delphi is committed to continue the path of Hybrid Brakes first followed by Full Brake by Wire second.

Local Suppliers / Universities Support

The following suppliers were contracted to support the project :

Circuit Pak Inc.	Dayton, OH
Circuit Center Inc.	Dayton, OH
MotorSoft	Lebanon, OH
American Precision	Troy, OH
Country Machining	Tipp City, OH
Buckeye Stamping	Columbus, OH
Newark	Dayton, OH
Future Active	Dayton, OH
Dayton Nut & Bolt	Dayton, OH
Pioneer Standard	Dayton, OH
Morgan Ceramics	Mass.
Milliat Industries	Kettering, OH
Bastech	Dayton, OH
Thaler Machining	Miamisburg, OH

SNI	Beavercreek, OH
American Precision	Troy, OH
Select Tool	Dayton, OH
Texas Instruments	Mass.
Sun Micro Stamping	Florida
IAP	Dayton, OH
McGregor-Surmount	Brookville, OH

The following universities were contracted to support the project:

Research	
University of Dayton	Dayton, OH

Deliverable Reports

Quarterly Reports

A report was generated quarterly summarizing financial and engineering status as well as outlining changes in the project plan. A total of 8 reports were submitted to the project administrator starting with 07-01-2001 and ending with 07-10-2003.

Design Reviews

A total of 3 design reviews were held to report in more technical detail the financial and technical progress. Reviews were held on 11-13-2001, 12-04-2002 and 06-26-2003.

Ride and Drive Event

A vehicle demonstration is scheduled for 09-16-2003. A GMC Envoy with a full Brake-by-wire brake system will be available for driving to demonstrate capabilities developed to date.

Financial Report

Resources Spent

The following costs were incurred over the duration of the project (summary provided by NCIC):
The following table lists the resource mix spending:

Technology Investment Agreement
Agreement No. F33615-01-2-5804
Effective Date: 11Jul2001
Resource Summary

	Total Amount	Federal Share	Recipient Share
Agreement Amount	$2,348,000	$1,174,000	$1,174,000
Costs incurred 7/11/01 - 9/30/01	$258,093	$124,377	$133,716
Costs incurred 10/01/01 - 12/31/01	$336,341	$172,840	$163,501
Costs incurred 01/01/02 - 03/31/02	$524,026	$262,013	$262,013
Costs incurred 04/01/02 - 06/30/02	$451,869	$225,935	$225,934
Costs incurred 07/01/02 - 09/30/02	$257,044	$128,521	$128,523
Costs incurred 10/01/02 - 12/31/02	$344,073	$172,037	$172,036
Costs incurred 1/1/03 - 03/31/03	$176,554	$88,277	$88,277
Subtotal	$2,348,000	$1,174,000	$1,174,000
% of Agreement	**100.00%**	**100.00%**	**100.00%**
Remaining	$0	$0	$0
	0.00%	**0.00%**	**0.00%**

	ACTUAL COSTS SPENT:	Complete Fiscal Year One	To Date: Fiscal Year Two		Total
A	Technical Personnel Salaries/Wages	427,951	173,641		601,592
F	Equipment	10,858	4,284		15,142
G	Material/Supplies	161,276	67,189		228,465
H	Subcontracts	6,000	-		6,000
I	Other	131,219	60,866		192,085
J	Total Direct Costs-LinesA thru I	**737,305**	**305,979**		**1,043,284**
K	Total Indirect Costs	916,802	388,301		1,305,103
L	Total Costs - Lines J + K	**1,654,108**	**694,280**		**2,348,387**
	NCIC Revised Format for Match Funds (50% of Total Costs)	**827,054**	**347,140**		**1,174,194**
	NCIC 7% Charged Support Fee	**57,894**	**24,300**		**82,194**
	Delphi Brake by Wire Funds Requested (93% of Match Funds)	**769,160**	**322,840**		**1,092,000**
	Memo: Total Costs (equals Line L Total Costs)	**1,654,108**	**694,280**		**2,348,387**
	Revised Recovery Rate Computed	**46.5%**	**46.5%**		**46.5%**

Payments

The following payment schedule was provided by NCIC :

Delphi - Brake by Wire TIA								
	NCIC (Recipient)				Delphi (subrecipient)			
	Amount	Requested	Received		Invoice No.	Date	Amount	Date Paid by NCIC
TIA	$1,174,000						$1,092,000	
Advances								
1	$61,844	10/17/2001	11/06/2001		1800001866	10/15/2001	$61,844	11/14/2001
2	$62,533	12/10/2001	12/20/2001		1800001881	10/24/2001	$62,533	12/31/2001
3	$55,127	12/10/2001	12/20/2001		1800001979	11/30/2001	$55,127	12/31/2001
4	$71,270	01/15/2002	01/28/2002		1800002002	12/13/2001	$53,716	02/14/2002
5	$46,443	02/07/2002	02/21/2002		1800002049	01/28/2002	$43,192	03/07/2002
6	$72,007	03/01/2002	03/12/2002		1800002100	02/27/2002	$66,966	03/27/2002
7	$82,757	03/26/2002	04/09/2002		1800002123	03/26/2002	$76,964	04/10/2002
8	$107,249	04/29/2002	05/08/2002		1800002197	04/29/2002	$99,742	05/17/2002
9	$105,759	06/03/2002	06/20/2002		1800002316	05/31/2002	$98,355	06/27/2002
10	$112,009	06/24/2002	07/08/2002		1800002370	06/24/2002	$104,169	07/19/2002
11	$8,167	07/26/2002	08/02/2002		1800002457	07/29/2002	$7,595	08/30/2002
12	$41,889	08/27/2002	09/11/2002		1800002598	08/29/2002	$38,957	09/27/2002
13	$31,517	10/01/2002	10/24/2002		1800002895	10/31/2002	$29,311	10/31/2002
14	$55,115	10/30/2002	11/14/02 & 12/17/02		1800002882	10/30/2002	$51,257	12/31/2002
15	$85,893	11/26/2002	12/12/2002		1800003001	11/27/2002	$79,881	12/18/2002
16	$63,205	01/21/2003	02/03/2003		1800003205	01/22/2003	$58,781	02/13/2003
17	$22,938	02/10/2003	03/17/2003		1800003384	02/07/2003	$21,333	03/19/2003
18	$71,989	03/11/2003	03/24/2003		1800003777	04/08/2003	$66,949	04/17/2003
19	$16,289	04/30/2003			1800003847	04/29/2003	$15,328	
Sub Total	$1,174,000						$1,092,000	93.02%
	100.00%						**100.00%**	
Remainder	$0.00						$0.00	
	0.00%						**0.00%**	

Intellectual Property Report

IP applied

Delphi applied for the following Intellectual Property protection:

- Potential invention ideas recorded----49 (*)
- U.S. patent applications filed 17 + 5 to be filed = 22 total (*)
- Defensive Publications--------- 1 (*)

IP granted

- U.S. patents already granted---1 (*)

(*) Data on this page as of 06/26/2003 (design review 3); up to date report was submitted separately from closeout report

Engineering Report

General

Over the 2 year duration of this project and with government funding assistance, a total of 2 design iterations for electric calipers and 2 systems (full brake by wire and hybrid brakes) were developed culminating in the demonstration of a fully integrated electric caliper and a full Brake by wire equipped Sports Utility Vehicle (GM Envoy).

Significant technical challenges remain before the technology will be available on vehicles in production, but a significant step towards producibility was made over the last 2 years.

Drive-able Brake-by-wire Concepts

Hybrid Design Options

A Hybrid Brake system is defined as a combination of a conventional hydraulically based brake system acting on the wheels of one axle and electric brakes acting on the wheels of the second axle of the vehicle.

In a **standard configuration**, the conventional hydraulic brake system actuates the front brakes and the electric brakes actuate the rear brakes. Brake system components include:

- Brake pedal with brake light switches and travel sensor or force sensor
- Apply system consisting of master cylinder and vacuum booster
- ABS/TCS modulator with integral ABS and electric brake electronics
- Front hydraulic brake calipers
- Rear electric brake calipers

Improvements as relating to a fully conventional hydraulic brake system include:

- Improved pedal feel i.e. brake pedal force is maintained while brake pedal travel can be shortened
- Push button park brake i.e. park brake lever and mechanism is replaced by a dash push button
- Vacuum booster smaller i.e. vacuum booster can be downsized by at least one size
- Functionality enhancements:
  - Regenerative brake blending support for rear wheel drive vehicles
  - Hill hold / launch assist
  - Traction control for rear wheel drive vehicles

In an **alternate configuration**, the conventional hydraulic brakes are acting on the rear wheels while the electric calipers are acting on the front wheels. The component set is identical to the standard configuration except that front calipers are electric and rear calipers are hydraulic.

Improvements also are similar to the standard configuration improvements with some important differences:

- Regenerative brake blending and traction control can now be applied to front wheel drive vehicles. This is relevant especially for regen brake blending as significantly more energy can be regenerated during braking from the front of the vehicle than from the rear of the vehicle due to dynamic weight transfer effects.
- The vacuum booster can be downsized by more than 1 size or for very small vehicles can potentially eliminated to support the cost versus value aspect of replacing a conventional brake system with a hybrid brake system
- Park brake can now be done using the front brakes with their higher clamp force capability

The challenges with this alternate configuration are to design and build a front caliper meeting all performance and reliability requirements cost effectively.

Full Electric Design Option

A variety of “Full Brake by Wire” design options were presented in detail during the design review. These design options will continue to be evaluated for safety, reliability, availability, installation ability, serviceability, diagnosibility, maintenance cost as well as acquisition cost. Some of these items including safety, reliability and others will be defined a minimum requirements while other parameters will be traded off against each other. OEM’s will most likely take the lead role in defining the production level architecture of the full brake by wire designs.

Manufacturing and Cost Analysis of System Development

Manufacturing processes and methodology focused mainly on the ballscrew and electronics component sets.

Costs are not discussed in detail within the context of this report as they represent Delphi Confidential Information. A discussion of the cost challenges follows in the next chapter.

Issues and Challenges

Cost

Delphi manufactures brake components and systems for high volume automotive applications. To operate effectively at the selected business model, typical volumes per brake assembly part number range in the 100k to 100s of k. Competitive pressure is very high (worldwide competition ⇔ overcapacity).

Hydraulic brake manufacturing and assembly into the vehicle was implemented in the 1920s / 30s and has reached a mature and optimized cost level making it quite challenging to introduce new technology on the basis of a lower cost level. Simultaneously, vehicle drivers are not typically willing to pay for new technology to brake a vehicle posing a challenge to introduce electric brakes on the basis of "new technology".

The opportunities to introduce electric brake systems into the vehicle of tomorrow are :

- Increasing value i.e. maintaining cost (at the brake system level) while increasing functionality to the vehicle driver (most likely requiring to operate at the chassis or vehicle level).
- Reducing cost at the brake system or component level while maintaining vehicle driver level functionality

Meeting costs of current mature brake systems and components while meeting driver expectations with respect to maintenance (the lack thereof actually), reliability, availability and performance is and continues to be the major challenge of this project.

Significant progress in closing the cost objective gap was made by introducing electric brake hardware on a single axle (hybrid brake system). However, due to the need for electrically based safety / redundancy for full electric brake system, a significant cost challenge remains for such systems.

Safety

When defined as an indicator for the ability of the brake system to stop the vehicle in fully functional, failed or partially failed modes, all indicators to date are that there are no significant differences between conventional hydraulic and BBW based vehicle effects overall.

There are no open regulatory issues in the US but some minor issues with EU regulations. Delphi will continue to work with European OEMs and monitor EU regulation development in order to find solutions meeting worldwide brake system safety regulations.

Reliability

Meeting the requirement to match reliability of the hydraulic brake system at the brake system level will continue to be one of the major challenges of this project Highlights of reliability challenges include but are not limited to:

- Temperature exposure: Simulations as well as on-vehicle tests indicate reasonable temperature levels for both long duration low apply profiles (mountain descents) as well as repeated short duration high apply profiles (racetracks). Long term effects such as exposure to repeated high end temperature exposure over the life of the car have not been demonstrated.
- Complexiity : A hydraulic caliper represents a relatively simple mechanical type part assembly at a high maturity level. Power in the form of hydraulic flow and pressure are converted to a clamp force through exposure to a surface: a straightforward process. The electric caliper however contains a significantly larger number of mechanical components, a fairly complex control module and associated mechanical / electronic interfaces. Power is provided in the form of

voltage / current and must than be converted through multiple devices including a brushless motor, gearing, ballscrews with associated time variable efficiencies. Also, the impact of the software controlling the assembly must not be underestimated.

- New technology: Some of the components designed into the caliper represent new technology to Delphi in their intended form and function. Relatively limited experience data is available and requires extensive development effort, testing and design. Dynamic simulations and Engineering analysis tools aid in gaining understanding and knowledge and are being widely used on this project. The evaluation / prediction of reliability has just begun. The ARMS (Allocated Resource Management System) process is utilized to predict system reliability as a function of time. ARMS is a representative of the reliability growth and prediction tool family and predicts the system level reliability on the basis of resources (bandwidth, background, organizational parameters, management support), a priori / experience knowledge as a starting point with continuously improving accuracy upon availability of test data. Examples: Motor and ballscrew

Test data is generated through bench tests (performance, mini durability test with Hardware in the loop), corner level dynometer tests (performance, durability) and full / accelerated Multi Environment Overstress System Tests (MEOST; durability). Resulting data utilized to calibrate the ARMS model.

MIL-217 is not being utilized for this project. Delphi has standardized on ARMS as the tool of choice for reliability prediction / control.

Installation

On vehicle installation and service is desired to be simplified but yet similar in process to a conventional hydraulic caliper.

Hydraulic screw type brake line connections are replaced by a single wiring connection to the vehicle harness. Park brake cable connection are also replaced by the same wiring connection significantly simplifying the vehicle build and service process.

Park brake cables do not need to be routed as separate cables along the floor board with associated hanger assemblies. Also, separate part numbers for different length versions of the same platform for park brake cables are not longer needed tin inventory and to be installed.

Basic installation of the caliper (floating caliper design) is identical to conventional hydraulic caliper installations.

Vehicle manufacturers are not likely to (significantly) modify the packaging of non-brake components inboard of the brake rotor for the purpose of packaging an electric caliper on the vehicle. The caliper therefore must package close to within the same envelope as a hydraulic caliper requiring several “design for packaging” iterations and resulting in very highly dense caliper packages. Meanwhile, the caliper must remain capable of low cost manufacturing and assembly.

Vehicle installation also drives the connector location to a significant degree reducing the design degree of freedom with respect to the integrated circuit board

High Temperature Electronics Development

Switching and conduction power losses in conjunction with temperature rises from the thermal resistances encountered by the power devices, may require a reduction in the Electric Caliper service motor's operational capability during certain brake profiles. Silicon carbide (SiC) and gallium nitride (GaN) power switching devices could potentially mitigate the problem of exposing with their higher maximum temperature limits. However, at present, only one major semiconductor manufacturer offers SiC power FETs and diodes products, with availability and substantially higher costs over silicon devices a major concern.

Another related area of concern is the durability and ripple current capability of the aluminum electrolytic capacitors used to filter the Vbattery bus in the motor drive section. Although manufacturers have made efforts to develop a low cost, high temperature, and high ripple current aluminum electrolytic solution for automotive applications, the diamond like carbon (DLC) dielectric would experience reduced self heating from high ripple currents due to low equivalent series resistance (ESR) and a longer life by absence of an electrolyte that dries out over time. Commercial availability and meeting cost targets are questionable at this time.

Use of a dedicated low cost DSP for motor control saved valuable board space and provided better performance/flexibility over a discrete hardware approach. With the proliferation of DSP /microcontroller devices with motor control peripherals, additional cost savings may be possible if one device could perform all of the hybrid controller tasks

With the lack of real high temperature electronic components available in the near future at commercially acceptable cost, effort was put into evaluating the use of high temperature automotive grade electronic components and the following conclusion was reached : A "high" temperature electric controller that is integral to the electric caliper is both technologically and commercially feasible using automotive/industrial temperature grade silicon semiconductors and conventional technology passive components.

A key design concept is the thermal isolation of the controller's heat sink from the caliper housing conduction path. This was achieved by use of a thermal barrier plate mounted between the controller and the caliper housing. By limiting the heat sink's maximum ambient temperature, the power switching devices can operate up to their 125deg maximum rating.

Reconfigurable Controls Development

Re-configurable control is a method of re-assigning the control tasks in the case of actuator failure(s) in such a way that the control objectives are still achieved with remaining actuators. In an effort to develop re-configurable control strategies on early stage of development, detailed and simplified models of brake by wire and steer by wire were created. They were incorporated into full vehicle simulation model, and also used in control system development.

Several versions of control allocation algorithms were proposed: one based on fundamental understanding of vehicle dynamics and relatively simple rules, the other on AFRL-developed optimization algorithms relying on a dynamic model of vehicle developed for this purpose. The simplified algorithms were developed for vehicle for brake by wire system only and for vehicle with brake and steer by wire. Vehicle performance under actuator failure was evaluated using high fidelity vehicle simulation model. The results indicated that in the case of vehicle with brake by wire only, vehicle with re-configurable control algorithm exhibited shorter stopping distances than the vehicle operating without the algorithm. More importantly, the algorithm improved dramatically vehicle yaw arte and path deviation caused by

asymmetric braking due to failure, thus making driving task easier. Further improvement of the stopping distance and reduction in path deviation was achieved in simulation, when vehicle was equipped with both steer by wire and brake by wire systems, and automatic steering correction was provided by the proposed algorithm. An optimal re-configurable control algorithm developed at AFLR was modified for application to the control allocation problem for drive-by-wire vehicle. It was integrated with the vehicle simulation environment.

Robust Force Sensor Development

An evaluation of sensor technologies was executed. The most promising technology was chosen and further developed. Results to date indicate no roadblocks to meet performance, reliability, cost and packaging specifications for Electric Caliper applications both front and rear.

Furthermore, given further development, this type of sensor has enormous potential from a robustness as well as cost perspective to replace numerous force/strain sensors in various applications (load, environment).

Fault Tolerant Architecture Development

A variety of full Brake-by-Wire and Hybrid Brake System architectures were presented including power generation and distribution, networking, sensor and actuator topologies. The Delphi System Safety Process was presented, discussed and applied to the chosen architecture up to current development level including single and dual voltage power distribution diagrams and mechanizations, power distribution state diagram, network and sensor diagrams, subsets of a fault tree analysis and reliability block diagrams, failure mode and effects analyses, hazard mode analysis and a hazard table.

Reliable Wiring and Connectors

Issues relating to automotive wiring and connections systems in general with respect to installation, reliability and warranty were summarized and presented during design reviews. Solutions based on best practices in the automotive field were reported.

The second major topic included a review of 42 volt related challenges and their resolution within automotive level cost targets including arcing, corrosion with salt water present as well as damage and arcing when connecting and disconnecting under power. Solutions presented included connector designs to control connection timing, sealing and circuit designs to avoid connecting under high potential differentials.